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A foray into laser projection and the visual perception of aircraft aspect

Keith K. Niall

Defence R&D Canada – Toronto
Technical Report
DRDC Toronto TR 2002-108
April 2002

Canada

20020828 209

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Abstract

High-resolution visual displays have been designed for flight simulation so that observers may judge the aspect angle of aircraft at far distances. The present experiment compares two display devices as untrained observers judge the spatial orientation of two target aircraft: F15 and F16 jets. The display devices are a prototype direct-write microlaser projector, and an SXGA format CRT display. Observers' accuracy of aircraft identification is better with the laser projector, and recognition response times are faster. A simple rule was found to fit the observers' response times: the rule is expressed in terms of a statistic on the autocorrelation of black and white silhouette images of aircraft. Observers' estimates of aspect are biased by the laser projector, while observers' estimates of aspect are accurate on average with the SXGA display. This bias in estimation of aspect may be attributable to variations in line brightness introduced by the laser projector.

Résumé

Des écrans de visualisation haute définition ont été conçus pour la simulation de vol afin de permettre aux observateurs de déterminer l'angle de présentation d'aéronefs à grande distance. Dans la présente expérience, on compare deux dispositifs de visualisation utilisés par des observateurs inexpérimentés pour évaluer l'orientation spatiale de deux aéronefs cibles : des avions à réaction F-15 et F-16. Les dispositifs de visualisation sont un prototype de projecteur à microlaser à écriture directe et un écran cathodique SXGA. La précision d'identification des aéronefs par les observateurs avec le projecteur à laser est supérieure, et le temps de réponse pour la reconnaissance est plus court. On a trouvé une règle simple adaptée aux temps de réponse des observateurs. Cette règle est formulée en fonction d'une statistique relative à l'autocorrélation des images silhouettes d'aéronefs en noir et blanc. Les estimations des observateurs quant à la présentation sont biaisées lorsque le projecteur à laser est utilisé, alors que les estimations faites avec l'écran SXGA sont généralement précises. Le biais sur l'estimation de la présentation peut être attribué à des variations de luminosité de ligne causées par le projecteur à laser.

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Executive summary

Fighter pilots can identify an aircraft several kilometres away by vision alone. There are differences in aspect angle and aspect rate that pilots can discriminate in the air, which cannot be displayed with an adequate number of pixels by the visual system of contemporary flight simulators. This requirement of more pixels for the visual display systems of military flight simulators has fuelled the development of new high-resolution visual displays. A microlaser-based display was constructed with a paintbrush type scanning architecture. The display used a monochrome green laser light source. An experiment was conducted to compare this display to a high-resolution CRT device, as observers identified and judged the orientation of depicted F-15 and F-16 aircraft. Some clear differences have been observed between the display devices. A definite prediction can be drawn for response times to the identification of the aircraft, as well. There are several specific conclusions that can be drawn from the results. They are:

1. Observers identified F-15 and F-16 aircraft more accurately with the microlaser projector.
2. Observers identified the aircraft more quickly with the microlaser projector.
3. When the aircraft were varied in aspect alone, F-16 aircraft were identified far more accurately overall. When the aircraft were varied in aspect and pitch together, this was not the case.
4. It took more time to identify aircraft when they were depicted to be further away.
5. Reversal errors were common in observers' judgments of aspect and pitch.
6. Despite its other advantages, the microlaser projector biased observers' judgments of aspect angle. This bias was pronounced when pitch was varied together with aspect angle.
7. Combined error in aspect and pitch was larger for the microlaser projector than for the CRT display.
8. Response times to identification of the aircraft vary neatly with a statistic on the autocorrelation of the aircraft silhouettes. This pattern is stronger for observers who identify the aircraft more accurately.
9. Estimates of aspect angle and pitch are largely uncorrelated with response times and the frequency with which the aircraft are correctly identified.

Niall, K.K. 2002. A foray into laser projection and the visual perception of aircraft aspect. DRDC Toronto TR 2002-108. Defence R&D Canada – Toronto.

Sommaire

Les pilotes de chasse peuvent identifier un aéronef à plusieurs kilomètres simplement à l'œil nu. Ils peuvent établir en vol des différences entre des angles de présentation et entre des vitesses de variation de présentation qui ne peuvent pas être affichées avec un nombre adéquat de pixels par le système de visualisation des simulateurs de vol modernes. La nécessité d'un plus grand nombre de pixels pour les systèmes de visualisation des simulateurs de vol militaires a mené au développement de nouveaux dispositifs de visualisation haute définition. Un dispositif de visualisation à microlaser a été construit avec une nouvelle architecture de balayage.L'écran utilisait une source de lumière laser verte monochrome. Afin de comparer cet écran avec un écran cathodique haute définition, on a mené une expérience dans laquelle les observateurs identifiaient des avions à réaction F-15 et F-16 représentés et évaluaient leur orientation. Certaines différences évidentes ont été observées entre les dispositifs de visualisation. On peut également prévoir de façon précise, par déduction, les temps de réponse requis pour l'identification des aéronefs. Plusieurs conclusions particulières peuvent être tirées des résultats :

1. Les observateurs ont identifié les avions à réaction F-15 et F-16 avec une plus grande précision à l'aide du projecteur à microlaser.

2. Les observateurs ont identifié l'aéronef plus rapidement à l'aide du projecteur à microlaser.

3. Lorsqu'on faisait varier seulement la présentation, les aéronefs F-16 étaient identifiés globalement avec une précision beaucoup plus grande. Lorsqu'on faisait varier simultanément la présentation et le tangage, l'identification n'était pas aussi précise.

4. Il fallait plus de temps pour identifier les aéronefs lorsqu'ils étaient représentés à une plus grande distance.

5. Les erreurs d'inversion étaient fréquentes dans les jugements des observateurs concernant la présentation et le tangage.

6. Malgré ses avantages, le projecteur à microlaser faussait l'évaluation des observateurs quant à l'angle de présentation. Ce biais était marqué lorsqu'on faisait varier simultanément le tangage et l'angle de présentation.

7. L'erreur combinée relative à la présentation et au tangage était plus grande avec le projecteur à microlaser qu'avec l'écran cathodique.

8. Les temps de réponse requis pour l'identification des aéronefs varient nettement en fonction d'une statistique relative à l'autocorrélation des silhouettes des aéronefs. Ce comportement est plus marqué pour les observateurs qui identifient les aéronefs avec une plus grande précision.

Niall, K.K. 2002. A foray into laser projection and the visual perception of aircraft aspect. DRDC Toronto TR 2002-108. Defence R&D Canada – Toronto.

9. La corrélation des estimations de l'angle de présentation et du tangage avec les temps de réponse et la fréquence à laquelle les aéronefs sont correctement identifiés est très faible.

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Table of contents

List of figures

List of tables

Acknowledgments

Harry Warner's report [7] has been cited with permission from the Warfighter Training Research Division of the U.S. Air Force Research Laboratory (AFRL). The development of the laser projector is part of a continuing team effort by the Air Force Research Laboratory and Defence Research & Development Canada (DRDC). I would like to thank Dee Andrews, Phil Peppler, and Byron Pierce of AFRL in particular. A summary of the DRDC project is given in [20]. The microlaser projector was constructed by staff of Laser Power Research in Del Mar, CA (now Photera Technologies, Inc.). Laser Power Research has requested the reproduction of a copyright notice, which runs:

Introduction

Fighter pilots can identify an aircraft several kilometers away by vision alone. They can distinguish its direction of flight too, and the rate of its turn. The direction of an aircraft's flight relative to an observer is known as its *aspect angle*, and the rate of turn is its *aspect rate*. (A definition of 'aspect angle' is given in Annex A.) Pilots need to assess aspect angle and aspect rate in order to execute basic fighter maneuvers. Pilots need to judge the relative speed of a distant aircraft to their own speed. They need to decide if the distant aircraft is turning in the same circle as their aircraft, as they need to decide whether that distant aircraft is turning more or less quickly than theirs. Pilots judge aspect angle and aspect rate by eye, and from these they judge the changing relations of the two aircraft in space. A common intention is to be positioned on the same turning circle as, but moving faster than the other aircraft. Pilots also use their general knowledge of aviation: identification of an aircraft's type elicits knowledge of its power and performance characteristics, which include how sharply it may turn. Still, aspect angle and aspect rate are judged for themselves, and pilots estimate them explicitly.

There are differences in aspect angle and aspect rate that pilots can discriminate in the air, which cannot be displayed with an adequate number of addressable pixels by the visual display systems of contemporary flight simulators. (Here are a couple of numbers to indicate the numbers of pixels required. If an F-18 aircraft is 56 feet long – about 17 m – and it is 4 U.S. nautical miles distant – about 7408 m – then it subtends only 48 minutes of visual angle in longest profile.) Flight simulators have been advertised as a relatively inexpensive instrument for training fighter pilots, especially for training them in maneuvers which are exceptionally difficult or dangerous to execute in the air. Historically, the addressable pixel count of visual displays has placed severe limits on pilot training with flight simulators. Aircraft depicted to lie at a distance of several kilometers may appear only as a shapeless clump of pixels on the display screen. Then a plane's aspect angle and aspect rate are indistinguishable, not for reasons of a pilot's visual acuity, but as a consequence of the coarse grain of the display. It isn't appropriate to compensate for the grain of the display by magnifying the image of the aircraft: that would misrepresent its distance, and its relationship to sky and ground. The distances that are cited are not extreme, in the sense that pilots can detect aircraft at greater ranges still. Hamilton and Monaco [1] report that when their pilots detected other aircraft by their exhaust smoke, they did so at an average of 7.64 nm ($\approx$14.1 km; this is an average over 122 engagements). When those pilots detected other aircraft as a dark spot contrasted against a bright sky, then the average detection distance was 5.67 nm ($\approx$10.5 km, 624 engagements). So the distances at which pilots may judge aspect angle and aspect rate are by no means at the limit of their detection ranges. There are many dynamic cues by which pilots may discern the presence of an aircraft or its type: some examples are vapor trails (contrails), exhaust smoke, glint from the canopy of a plane, afterburner illumination, and power characteristics (i.e., how quickly the plane turns – a plane may be identified as a powerful model if it performs a very sharp turn). It should be noted that detection of air targets by pilots is better than their detection of surface targets [2].

Flight simulators perform many functions, and the addressable pixel count of a visual display may seem a small consideration in a larger context of pilot training. But a paucity of pixels may have a pronounced effect, if it leads pilots not to trust their eyes. The discrimination of small differences in aspect angle or aspect rate may not be attempted during flight, if the discrimination of those differences cannot be trained during simulation. The reduced or relatively impoverished conditions of observation inside a simulator may lead pilots to make less than best use of their abilities. It may lead to a change in their criteria for evaluating the spatial relations of their aircraft to others. In other words they may come to ignore the evidence of their eyes in the very situation for which they have been trained.

This requirement of greater pixel count for the visual display systems of military flight simulators has fueled the development of new high-resolution visual displays. The goal of this development effort is to produce displays which have an order of magnitude better pixel count than high-definition television, or stated in terms of pixels: 5000 x 4000 pixels or more. It should be noted that there is more to the creation of a high-definition display than pixel density: improvements to fine positional accuracy can be achieved in other ways [3]. Of course such displays find application in many other domains: a prime example is the development of digital cinema. An additional but separate problem is how to provide the image generation capacity to deliver such large images to a screen at a reasonable frame rate. There are several different technologies that have been brought to bear on the development of high-resolution visual displays. The technology that we have applied (for names see the Acknowledgments) to provide better pixel count in visual displays is the manipulation of light from small solid-state lasers. This class of devices is known as direct-write microlaser projectors. The present article describes a prototype projector, and an experiment on aircraft identification. The experiment was run with the prototype projector, and also with a CRT display of SXGA pixel count. The aim of the study is to address questions of relevance more or less directly: to ask if this projector will help observers to judge the static aspect of distant aircraft.

Claims have been made about 'eye-limiting resolution' with other display devices; those other claims are often ill-founded not for considerations of pixel count, but for lack of consideration of the surprising acuity that can be demonstrated by human observers. The kind of test that tends to accentuate a human observer's acuity is the vernier acuity task: an observer's ability to tell if two abutting vertical line segments are perfectly aligned, or if they are very slightly offset (to a fraction of the width of the lines themselves, in arcsecond magnitudes). But there is a sense in which those kinds of experimental manipulations miss the point of applied concerns about acuity in the context of a pilot's occupation and in military flight simulation: it is not the purpose of these displays to enable pilots to judge vernier alignments.

Instead we may address the problem that gave rise to concerns about acuity. That problem is the judgment of aspect for aircraft that are pictured to stand at a distance of many miles from the observer. Photographic images of standard aircraft (a set of profiles of F-15 and F-16 aircraft) have been generated from existing models, and these aircraft are pictured at different profiles. They are presented at different tilts and slants in space with respect to the observer. A set of these images was displayed with the microlaser device. The observers' task is to identify each image as being that of one of the aircraft (say, as an F-15 or F-16) at a given distance. The observer is asked to identify the aircraft under change in aspect at simulated distances from one nautical mile to three nautical miles. (One U.S. nautical mile = 6076.1 ft ≈ 1.852 km) Another task for the observers is to match the aspect angle of the aircraft in question to the depicted spatial orientation of a simplified or abstract model. A trained observer's ability to judge the aspect of an aircraft varies: if the aircraft is changing in aspect (i.e., turning), its aspect may be judged out to a longer distance than the aspect of an aircraft that is not turning. One may expect to judge the fixed aspect of an F-15 size target at roughly three nautical miles; similarly, the fixed aspect of an F-16 size target may be judged at roughly two nautical miles. These are minimum requirements for ranges at which one may be required to judge aspect angle. These rough distances correspond to the ranges for basic fighter maneuvers in a neutral (nonhostile) situation: the range for two-circle maneuvers is from 15,000 ft to 17,000 ft (≈4.6 km to ≈5.2 km [4]). Response times in this task and the number of correct responses to a silhouette may vary with the set of aircraft presented: that is a secondary concern. What is important is to know how limiting factors on an observers' ability to judge aspect angle and range can vary between display devices. The same set of judgments should be made with the microlaser device and a high-quality CRT device, for purposes of comparison. In this way greater realism in testing may lead to fuller generalization of conclusions drawn from a simple experiment, towards application in training simulators.

The prototype of a new technology

There are several features of microlaser projectors which make them promising for application in military flight simulation. Powerful and lightweight laser light sources are being developed: among these are novel solid-state laser devices. These devices can produce much smaller spots of light – that is, much smaller pixels – than conventional display devices. The brightness and long life of these light sources adds to their attraction. More important to psychological concerns is their characteristic as sources of narrow-band spectral light. With appropriately chosen wavelengths of light, a trichromatic microlaser projector can provide a range of colours – a colour gamut – of much greater range than has been the norm with other projector technologies. Yet there is another feature of these projectors which is of interest to students of visual form perception: these projectors can process several lines of a frame of imagery simultaneously.

Direct-write microlaser-based displays illuminate pixels in a way that is dramatically different from conventional CRT displays and active-matrix LCDs. Parallel-scan, microlaser-based, direct-write displays employ a scan architecture in which multiple beamlets of light are modulated and then scanned in parallel. The particular pattern in which these lines are scanned will change the apparent coherence of the image. During the scan, a galvanometer scanner may move the group of beams down so that when the second group is scanned, they are shifted down by the appropriate amount. The effect of this pattern will interact with the pixel frequency and frame rate of the display to affect the coherence and fidelity of the image with respect to a static snapshot or the output of an image generator [5,6]. These artifacts manifest themselves as image fragmentation or breakup. Whenever a snapshot scene is painted in time-sequential fashion, the apparent geometry of moving objects is distorted. In a typical parallel-write system, adjacent lines can be written at times which are separated by intervals much greater than the time required to write a single line. The apparent coherence of these images to an observer is also affected by some machine-independent factors, such as saccadic eye movements and oscillatory movements of the observer's head. Image fragmentation and breakup of this kind are not acceptable for displays used in flight simulation.

There are several solutions to this sort of problem. One is to develop a spatial light modulator – also known as a light valve – that can process an entire line of imagery at once. That is, an entire column of a frame of imagery is written simultaneously; there are as many elements to the light valve as there are pixels in the height of the image frame. This arrangement would not evince the sort of image deformation that has just been discussed. But with this arrangement, there is another danger: suppose that a single element of the light valve is not working, or that for some reason it delivers a reduced brightness of light. Then there will be variations in brightness between lines of the projector image. A projector can be calibrated to eliminate or moderate such variations in brightness, but they are a problem for any parallel-write display of this kind that may be designed. Such artifacts can have serious consequences, as we shall see in the results of an experiment.

An experiment

The aim of the present experiment is to compare two display devices as observers identify and also judge the orientation of depicted F-15 and F-16 aircraft. The interest of the results is in an account of the discrimination of the orientation of self-occluding objects in space, as well as in these displays. The experiment uses a set of images of F-15 and F-16 models that was developed for Warner et al. [7]. Some of these images are shown in Figure 1.

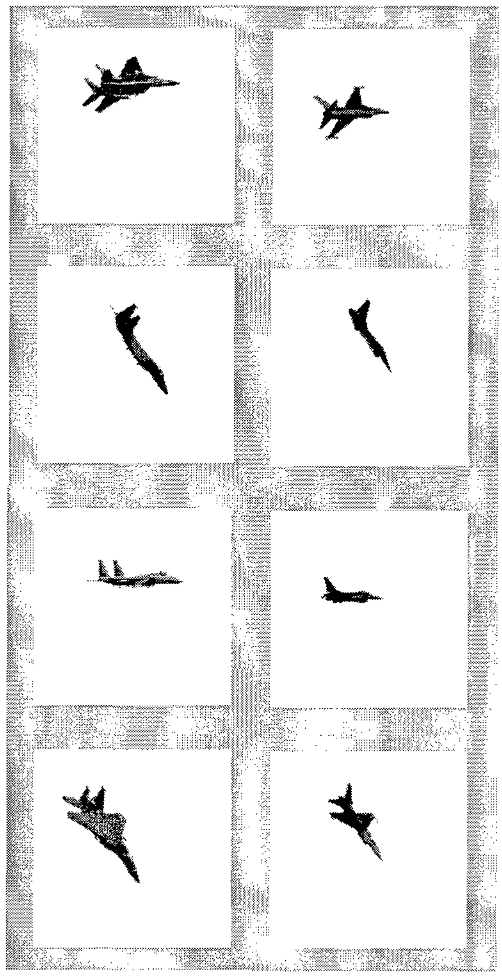

Figure 1. *Changes in spatial orientation and in aircraft type define sixteen images of F-15 aircraft and sixteen images of F-16 aircraft. Some of these images of F-15 aircraft appear in the left column; some images of F-16 are in corresponding orientation in the right column. The aircraft are in order from top to bottom, in the orientations listed explicitly as rows 13 to 16 of Table 1.*

In their study, they sought to discover the visual cues that pilots use to discriminate such aircraft at a variety of spatial orientations and distances. They used slide images of F-15 and F-16 models (1/48 scale), photographed to represent distances of 1 nm, 2 nm, and 3 nm. "The rationale for using these four distances is that they are representative of the distances involved in the target orientation and assessment phase of air combat training." [7, p.10]. They recruited 80 USAF active-duty and reserve fighter pilots, and showed them these images by tachistoscope. Each image was shown for five seconds. Warner et al. [7] manipulated the variables of aircraft orientation, aircraft type, depicted distance from the observer, pilot flight experience, and the plane type flown by the pilot. The investigators recorded the frequency of correct responses, that is, they chose accuracy of identification as a dependent measure. They also asked pilots to report the features of the aircraft that they used to distinguish the planes in the images. The investigators seem to draw conclusions about the pilots' ability to discriminate the orientations and distances of the aircraft, though the form of their data was the frequency of correct responses. "The analyses of the target orientation responses... indicated that the differences in response accuracy between pilot types was negligible and that there was no effect of pilot's aircraft type on the response accuracy when the 16 target orientations were pooled."[7, p.18]. The investigators found that the aircraft were more difficult to identify when greater distances were depicted. They also found that the larger F-15 planes were more easily identified than the F-16 planes, though their relative frequency of correct identification varied with increasing distance. They also found that the F-15 planes were more accurately identified at a pitch angle than were the F-16s.

Warner et al [7] go into some detail about the features that pilots report using to identify the aircraft. They sorted these reports by the number of correct identifications associated with them: eleven parts of the aircraft were found to have the greatest influence on correct identification overall. In order, these were: the tail of the plane, its wings, the nose, the intakes, the planform, the canopy, the belly, missiles, the top of the aircraft or of the wings, the fuselage, and the exhaust outlets. The planform may be a more important feature than its position in the list indicates. The authors distinguished 'planform' features from 'silhouette' features: both kinds of features contributed to correct identifications, and together they represent a very strong contribution. The authors explain their distinction [7, p.18] as follows: "Strictly speaking, the term silhouette refers to the outline or contour, whereas planform refers to the outline of an aircraft when looking at it such that the wing shape is distinguishable."

They emphasize the importance of silhouette or planform in identification of the aircraft from these images, when they say: "... a clearly defined aircraft outline is essential to accurate aspect recognition at 3.0 nm". The distance they mention is the furthest viewpoint they use.

The present experiment uses a subset of Warner et al. [7] images. Their largest images of planes – those depicted to lie at 0.5 nm – were not used here. The present experiment has two major features that were ignored in the earlier study: observers' response times to identification are measured, and observers are required to estimate the orientation of the aircraft in the picture.

Observers

Subjects were recruited from the University of California, San Diego and the surrounding community. None were familiar with laser-based displays; they were paid for their participation. The subjects had at least 20/20 Snellen acuity, or acuity corrected to 20/20, and they had no personal or family history of seizure disorders. Subjects were assigned randomly to two groups. Of the 21 subjects admitted to the experiment, 12 were male and 9 were female. Their average age was 33. Each subject was required to participate in 8 sessions for the aircraft identification task. The 15 subjects who completed the experiment took 11.5 hours on average over eight sessions: these times include coffee breaks and lunch breaks.

Stimuli

The experiments were conducted with 50-lux ambient halogen illumination in the experimental room. The monochrome green laser display operated at 0.4 fL, measured by conventional methods. The CRT display (monochrome G signal only) was dimmed to operate at 0.4 fL. Subjects were seated at about 60 cm (24 inches) from the display screen for either the CRT or the laser display. (The laser display was rear-projected onto a screen.) Both displays subtended 22° by 28° of visual angle from the observers' position. The software program presented bitmap (.bmp) images of 1280 X 1024 pixels.

Two aircraft types (F-15 and F-16) were presented at sixteen different orientations: see Table 1 for specification of these distinct orientations in space. Each of these orientations was represented at three relative distances (of 1 nm, 2 nm, and 3 nm: a U.S. nautical mile is 6076.1 feet, which is 1.852 km). The relative distances may also be construed as representing the relative sizes that are projected by the aircraft models on the screen. The sizes on the screen were larger than would be projected by aircraft at such a distance; image sizes were matched between the microlaser projector and the CRT device. The actual length of the F-15 is 63 ft 9 in (≈19.4 m), and its wingspan is 42 ft 10 in (≈13 m). The actual length of the F-16 is 49 ft 3 in (≈15 m) and its wingspan is 32 ft 10 in (≈10 m, including missile fins). The experimenter who administered the protocol was unaware of the specific conditions of orientation administered during the experiment.

Two aircraft types or *Plane types* were depicted in the experiment: F-15 and F-16. The aircraft were depicted in sixteen different orientations. These sixteen orientations included eight different angles, or *Aspect*s. The notion of aspect angle is described further in Note 1. The orientations also paired each aspect angle with another rotation, or change in *Pitch.* This depicted rotation was either present or absent at each of the aspect angles. Each of the F-15 and F-16 images was presented at three relative sizes or *Depicted distances*, to show the effect of increasing standoff distance. Each of these images was presented to an observer four times, at different locations on the display screen. That is, the airplane images were not centred on the display screen, but were presented halfway towards the top, the bottom, the left-hand side, and the right-hand side of the screen. (Observers had been asked to fixate a dot at the centre of the screen before each presentation.) These locations on the screen are known as *Target locations*. The order of these conditions was randomized over days for each observer. Each observer saw all the images on the two display *Device*s, that is, the microlaser display and the CRT device. An observer completed all trials on one device before proceeding to the other device; the order of administration of the devices was randomized across subjects. This assortment of the experimental trials was divided across four days. The first two days were devoted to one display device, and the other two days were spent on the other display device. The experiment has a six-way (2 x 8 x 2 x 3 x 4 x 2, that is, *Plane type x Aspect x Pitch x Depicted distance x Target location x Device)* fully-crossed repeated measures design. That is to say, there were a total of 768 trials over four days for each observer in the experiment.

Table 1. *Sixteen orientations of the aircraft in space.*

ORIENTATION	ASPECT ANGLE	PITCH ANGLE	BANK ANGLE	DIRECTION
1	0	0	0	Tail-on
2	0	45 up	0	Tail-on
3	180	0	0	Nose-on
4	180	45 up	0	Nose-on
5	90	45 down	0	Left
6	90	0	60 left	Left
7	90	0	60 left	Right
8	90	45 up	120 left	Right
9	45	0	45 left	Left
10	45	45 down	0	Left
11	135	45 up	45 right	Left
12	135	0	45 left	Left
13	45	0	45 left	Right
14	45	45 down	45 right	Right
15	135	0	0	Right
16	135	45 down	0	Right

This table lists the aspect, pitch, and bank angles which define the sixteen orientations used in the experiment. These data are reproduced from Table 5 of [7]. Pitch angle up means positive angle in Figure 7; pitch angle down is negative. Bank angle left means counterclockwise for a forward-facing pilot of the depicted aircraft; bank angle right means clockwise in the same fashion.

Devices

A display was constructed that used a paintbrush type scanning architecture: 64 lines of the images were scanned at once. The experiment was conducted where the display was built: at Laser Power Research in Del Mar, California. The device is pictured in Figure 2. Construction of this display was the culmination of a lengthy optical engineering development. Fink et al. [8] have summarized that development. The display used a microlaser light source, a linear array modulator consisting of 64 elements, a scanning system to produce a pixel count of 1280 x 1024, video electronics, and optics to present a 17" image (≈ 43 cm). A microlaser-based display was assembled on an optical bench (a 'breadboard'). The light was generated by a green microlaser whose wavelength is 532 nm. The initial power of the laser was approximately 2W (split into two beams). The beam then passed through several optical elements, including a waveplate, a cube polarizer, and a Powell lens. The latter element is an aspherical cylindrical lens that expands a Gaussian circular beam into a linear band with uniform intensity along its length – the beam remains Gaussian along its width. This band of light is then collimated, and it enters a microlens array. That array consists of 64 adjacent lenslets that focus the beam into 64 spots (which correspond to the 64 lines of the image). The beamlets are then subject to a spatial light modulator, and recollimated. That is, the many parallel laser beamlets passed through what is known as a linear spatial light modulator, or a light valve. The spatial light modulator modulated the intensity of the beamlets separately in analog manner.

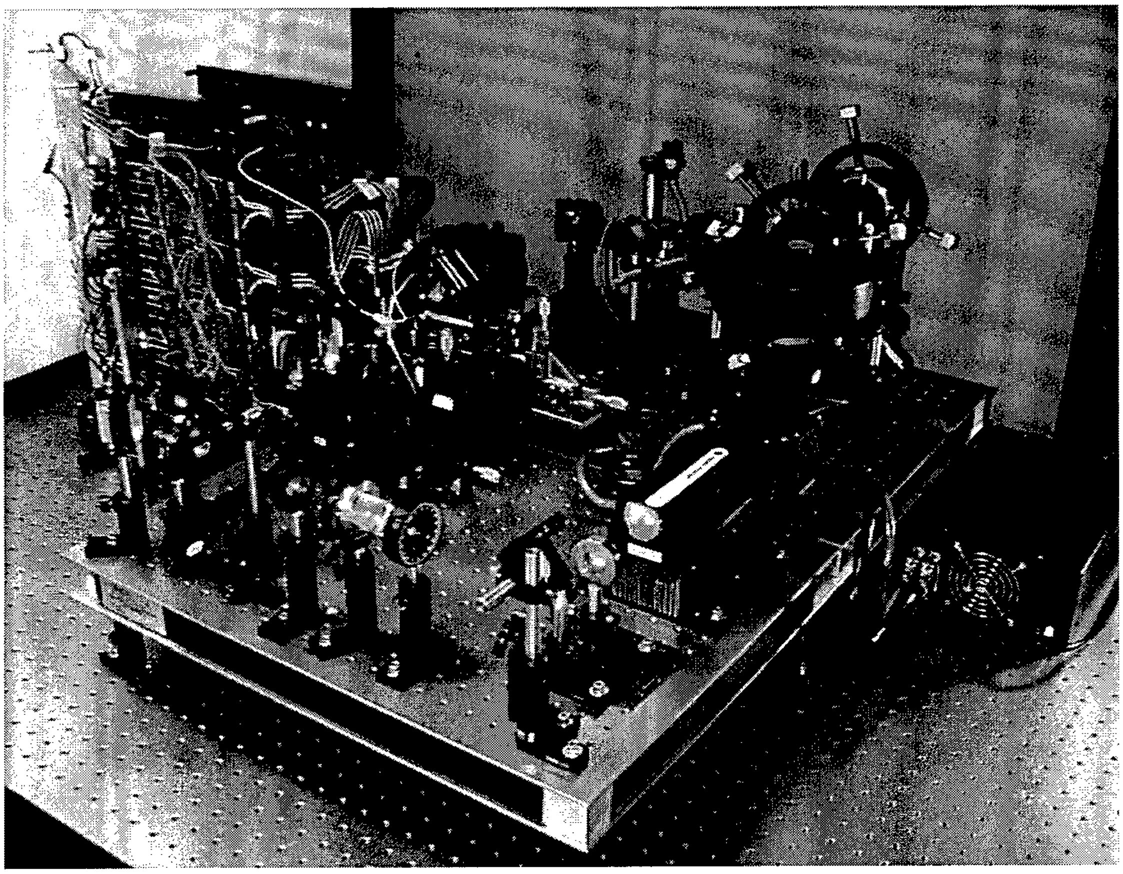

Figure 2. *A photograph of the microlaser projector, as it was mounted on an optical bench at Laser Power Research. This is a view from behind the screen, and looking towards it. The optical system projected a monochrome green image by the modulation of many lines of laser light.*

The scan pattern or scan architecture chosen for this display is a paintbrush configuration in which a group of 64 adjacent lines are scanned simultaneously. The beamlets are scanned in two ways to form the image: by a polygon scanner, and by a galvanometric scanner. During the scan, a slower galvanometer scanner moves the beams down, so that when the second group of lines is scanned, they are shifted down by the appropriate amount. The polygon scanner is a facetted and flat but thick polygon, that spins quickly about its center (in this case, at 3600 RPM). The edges of the polygon are mirrored to reflect light. The light was reflected from the polygon immediately from a galvanometric scanner. The motion of the polygon corresponds to the progress of the beamlets left to right across the image screen; the motion of the galvanometer corresponds to successive groups of beamlets arranged vertically on the image screen. The polygon scans the beam into a commercially available scan lens (an f-θ lens), to produce equally spaced pixels at the image plane, and from there to a projection lens. The projection lens magnifies the image and projects it onto the display screen to form a 17” diagonal image. This laser projector has the same line rate as the SXGA display. While future laser projectors can achieve a much higher pixel count, CRT projectors are limited in principle.

The laser display image had some significant artifacts. The first artifact of note consisted of horizontal bright and dark bands due to non-uniform illumination. These bands may have been caused by non-uniformity in the response of the spatial light modulator, or in the polarizing elements. The second artifact consisted of bright retrace lines. Since the "off-state" of the modulator elements was not dark enough, these retrace lines were visible against the rest of the display. Because the response of the galvanometer scanner was not sufficiently fast, three bands were needed for the retrace. Nor did the bands line up uniformly across the display, so that there were gaps between some of the bands at the top and the bottom of the display. Each section of 64 lines has several lines that do not go into a dark state, which show as bright horizontal bands. This may have been caused by non-uniformities in the modulator, or else stress in other elements that are between a pair of polarizers. Finally, the image was dim, because of a reduction in the voltage input to the light valve, implemented to reduce noise in the electronics. There were 64 beams modulated at once, and this resulted in an extremely noisy electronic environment in which the other electronics boards necessary for the display would not have functioned. Therefore the 'depth of modulation' was diminished by applying a lower voltage to the modulator; this resulted in a dimmer image.

A Datel Pentium PC was used to provide imagery for both the CRT display and the laser display; the PC ran at 200 MHz with 128 Mbytes of RAM. An EIZO Nanao FlexScan 17-inch monitor (Cypress, CA: Eizo Nanao Technologies) was chosen as the CRT monitor; it displayed images at 1280 x 1024 pixel count (SXGA format). The monitor was interfaced to a Matrox Millenium II video adapter card with 8 Mbytes onboard memory. The observers used a mouse as the input device. The projected image of the laser display was set to be 17" diagonal, making it equivalent in size to the CRT monitor. The brightness of the CRT was turned down to be closer to that of the laser display.

Procedure

The software program presented bitmap (.bmp) images of 1280 X 1024 pixels. The program could be paused at any time during the trial sequence; when a pause was requested, the program completed the trial underway, and continued to the next scheduled display of the fixation dot on a black screen. The subject responded first by clicking the left or right mouse button to indicate whether the aircraft image was of an F-15 or an F-16. This left-right order was varied across subjects. Next, the observer indicated the orientation of the aircraft, using an attitude indicator. The attitude indicator was a graphic element of the display, pictured in three dimensions. This attitude indicator consisted of a long thin cylinder, black on one end and gray on the other. This thin cylinder intersected and was partially occluded by a small sphere (one might call this a ball and stick). Movement of the mouse in the $\underline{x}$ direction rotated the attitude indicator in the plane of the screen; movement of the mouse in the $\underline{y}$ direction was accompanied by a depicted rotation in depth of the attitude indicator. The gray end of the cylindrical bar indicated the nose of the aircraft; the black end of the bar was used to indicate the tail of the aircraft.

A screen that was blank except for a fixation dot preceded each trial. Subjects fixated on the circular dot in the center of the screen. Shortly after the dot disappeared, an image of an aircraft appeared on the screen. The aircraft could appear in any of four areas of the screen: the top, bottom, left, or right. The subject responded by pressing either the left or the right mouse button, to indicate either an F-15 model or the F-16 model aircraft. A response time was recorded, that is, the time between the initial presentation of the image and the time at which the mouse button was pressed.

The program measures time with accuracy on the order of milliseconds (less than the refresh time of the display screens, it should be noted). After the subject indicated the type of the aircraft (F-15 or F-16), the ball and stick appeared on one side of the display screen. Observers moved the computer mouse to indicate the direction and orientation of the aircraft. Once the observer was satisfied with his or her match of the orientation and direction of the aircraft, a mouse click terminated the trial and initiated a new trial. Though response times were recorded, observers were not under pressure of time to make their judgments.

Each observer saw 192 images of aircraft in each sitting or session; each subject was shown a total of 768 images with the two displays. Each subject saw all the stimulus images on each platform; the trials for one platform were complete before the subject began trials on the next platform. Since 15 observers participated in the experiment, the data set for the experiment consists of 11520 observations in all.

Results

Several dependent measures were considered in the analyses of data. The accuracy of observers' judgments was given in terms of frequencies of correct and incorrect identifications of the aircraft. The observers' response times were considered, as were those response times after they were log-transformed. The deviations of the observers' estimates in aspect are assessed with respect to the aspect of the aircraft models: these deviations were measured as the cosine of the difference between the aspect angle represented by the estimate (with the attitude indicator) and the aspect angle of the aircraft model. Similarly, the deviation of the observers' estimates in pitch was measured as the cosine of the difference between the pitch of the estimate and the pitch of the aircraft model. These two dependent measures were combined also, into the cosine of the difference in angle between estimate and model. The cosine transformation is a simple way of respecting directions over the circle. Methods for the treatment of directional data have been set forward in [9] and [10].

One of the dependent measures is the natural logarithm of response time. The principal motivation for applying the logarithmic transformation is the treatment of long outlying response times. The effect of the transformation is not gross over the range in question; its effect is that the distribution of response times becomes less skewed, and the tails of the distribution become more symmetric [11]. Times are included for all responses: that is, no 'trimming' of outlying response times has been applied over and above the logarithmic transformation. And unless otherwise stated, response times are included both for correct responses and for trials on which an error occurred.

The dependent measures have some simple relations one to another. The frequency of correct response is related to the ln response time for a condition, simply because correct responses are associated with shorter response times overall than incorrect responses. (There were 8639 correct responses among all responses for 15 observers in the experiment: the mean of those ln response times was 0.83 ln sec, with a standard deviation of 0.66. The 2881 incorrect responses had a mean of 1.21 and a standard deviation of 0.71.) The greater the proportion of incorrect responses for an image, the longer will be the response times on average. But ln response time does not covary with the measures of error in judgment of orientation, the way it covaries with frequency of correct response. The measure of ln response time has a negligible correlation to the measure of deviation in observer's estimates of aspect (Spearman r: -0.02, n = 11520) and the measure of deviation in observer's estimates of pitch (Spearman r: -0.06, n = 11520). By contrast, those latter two measures of observers' estimates have a robust relation to one another (Spearman r: 0.43, n = 11520). Often the frequency of correct judgments as in [7] or the speed of judgments has been taken as an index of an observer's ability to judge an aircraft's orientation in space. In other words, errors in the judgment of aspect and errors in the judgment in pitch have been supposed to have a reliable relation to measures of accuracy and speed in the identification of aircraft. Yet if these dependent measures are uncorrelated or unrelated, such an inference may not be warranted.

A general observation can be made from an overview of the experimental results: observers were more accurate in the identification of aircraft images with the microlaser projector than with the CRT display. A first impression of this difference can be obtained by computing overall *d'* scores for each observer on each device. The *d'* statistic is known as a measure of sensitivity that takes into account both correct identifications and false positive judgments [12]. Two *d'* scores were computed for each of the 15 observers: each *d'* score is based on 384 judgments by one observer. There are marked differences between the *d'* score for identification with the microlaser device and that for the CRT display: those scores are listed in Table 2. A larger *d'* score indicates better sensitivity. All but one of the scores for the microlaser device are above a *d'* score of 1.0, and most of the scores for the CRT device are below 1.0. (The exception in the *d'* score for the microlaser device is Observer 15, who did not seem to be able to discriminate the two aircraft in either condition.)

Table 2. *D' scores for each of the fifteen subjects, and the two display devices*

	OBSERVERS														
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***
A	0.43	0.04	0.08	0.48	0.50	0.38	0.68	1.07	0.41	0.24	0.41	0.63	0.63	1.00	0.11
B	2.26	1.36	1.23	1.74	2.41	2.80	2.30	3.19	1.48	1.43	2.55	2.97	1.98	3.24	-0.23

A = CRT, B = microlaser display. Observers are more accurate in their responses with the microlaser projector than with a CRT display. Each d' score is based on 384 judgments by an observer. D' scores for the microlaser device indicate good discrimination of F-15s and F-16s by the observers: the scores are well above 1.0. There is a marked difference in d' scores between the two displays – with the exception of those for observer 15, who did not seem to discriminate the aircraft on either display.

Let us take a more comprehensive look at the data. A six-way analysis of variance was computed for each of these five dependent variables: the logarithm of response time *(ln* *seconds*), the untransformed response time (*seconds*), the number of correct responses (*frequency correct*), the cosine of the difference in aspect estimates (*cosine Δaspect*) , and the cosine of the difference in pitch estimates (*cosine Δpitch*). Each of these analyses was a fully-crossed repeated-measures design. The independent factors were: *Plane Type, Target Location*, *Device, Depicted Distance*, *Aspect*, and *Pitch*. Table 3 provides a summary of these analyses that lists all significant factors and interactions.

***Table 3.** A summary of the results of five analyses of variance*

MEASURE	FACTOR	F VALUE	MSE	P
ln seconds	A	$F(1,14) = 12.84$	0.901	$p < .01$ *
ln seconds	C	$F(1,14) = 37.20$	24.339	$p < .0001$ ***
ln seconds	D	$F(2,28) = 59.16$	1.381	$p < .0001$ ***
ln seconds	F	$F(1,14) = 56.08$	0.683	$p < .0001$ ***
seconds	C	$F(1,14) = 33.10$	396.37	$p < .0001$ ***
seconds	D	$F(2,28) = 13.61$	110.34	$p < .01$ *
seconds	F	$F(1,14) = 9.50$	104.25	$p < .01$ *
# correct	C	$F(1,14) = 88.58$	2.213	$p < .0001$ ***
# correct	D	$F(2,28) = 74.22$	0.191	$p < .0001$ ***
# correct	E	$F(7,98) = 11.63$	0.171	$p < .01$ *
# correct	A x E	$F(7,98) = 9.77$	0.400	$p < .01$ *
# correct	A x F	$F(1,14) = 11.31$	0.751	$p < .01$ *
# correct	E x F	$F(7,98) = 18.35$	0.199	$p < .001$ **
cosine Δaspect	C	$F(1,14) = 26.28$	1.480	$p < .001$ **
cosine Δaspect	E	$F(7,98) = 13.76$	2.425	$p < .01$ *
cosine Δaspect	F	$F(1,14) = 15.15$	1.880	$p < .01$ *
cosine Δaspect	C x E	$F(7,98) = 18.58$	1.476	$p < .001$ **
cosine Δaspect	C x F	$F(1,14) = 16.85$	1.439	$p < .01$ *
cosine Δpitch	C	$F(1,14) = 23.97$	6.116	$p < .001$ **
cosine Δpitch	C x F	$F(1,14) = 13.45$	0.801	$p < .01$ *
cosine Δpitch	E x F	$F(7,98) = 12.03$	1.021	$p < .01$ *
cosine Δpitch	C x E x F	$F(7,98) = 11.83$	0.989	$p < .01$ *

A = plane type, B = target location, C = device, D = depicted distance, E = aspect, F = pitch. The five analyses correspond to five different dependent measures: 1) the logarithm of response time to aircraft identification (ln seconds), 2) the untransformed response time (seconds), 3) accuracy of identification, which counts 1 for correct identification and 2 for incorrect (# correct), 4) the cosine of the difference between the estimated aspect angle of the aircraft, and its actual aspect angle (cosine Δaspect), and 5) the cosine of the difference between the estimated pitch of the aircraft and its actual pitch (cosine Δpitch). Each of these is a six-way fully-crossed repeated measures analysis of variance. The significant factors of the analyses are tabled.

A six-way analysis of variance showed significant effects of *Device*, ($\underline{F}(1,7) = 9.55, p \leq .05$) *Depicted Distance*, ($\underline{F}(6,42) = 28.92, p \leq .01$) and *Aspect*, ($\underline{F}(6,42) = 28.92, p \leq .01$) on the dependent measure of frequency of correct response (*frequency correct*). There were also significant interaction effects of *Plane Type x Aspect*, (F(7,98) = 9.77, $p \leq .01$). *Plane Type x Pitch* (F(1,14) = 11.31, $p \leq .01$), and *Aspect x Pitch*, (F(7,98) = 18.35, $p \leq .001$). The Greenhouse-Geisser correction was applied to the degrees of freedom used to obtain the critical F statistics for these comparisons [13]. This conservative criterion will be applied in all further significance levels reported for analyses of variance. More correct identifications were made of images on the microlaser projector than on the CRT device (Figure 3). As relative size due to depicted distance increased, the frequency of correct identification decreased. There were complicated interactions of spatial orientation and plane type on frequency of correct identification. There is an interaction of plane type and pitch: though F-16s were identified more accurately in the absence of pitch (proportion incorrect of F-15s: 28.9%; proportion incorrect of F-16s: 21.1%), yet F-15s were identified as such more often for those images that showed pitch (proportion incorrect for F-15s: 23.5%; proportion incorrect for F-16s: 26.6%).

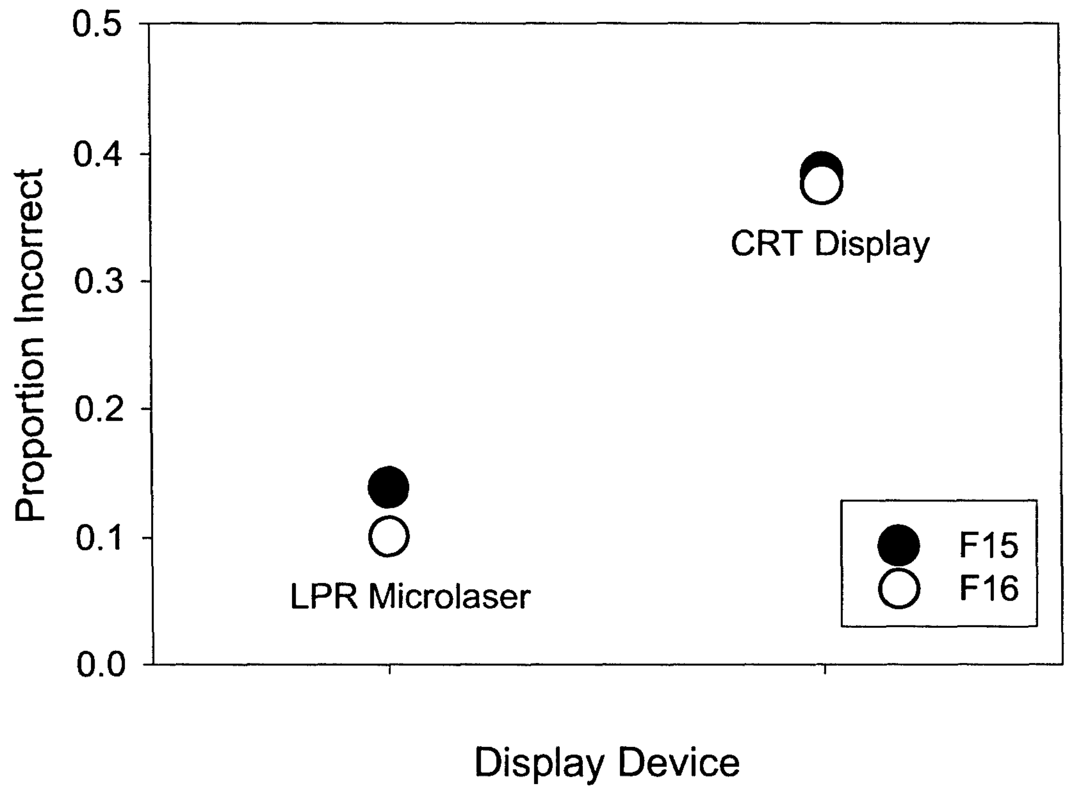

Figure 3. *Aircraft identification was more accurate with the microlaser projector. The proportion of errors in identification was notably lower when observers viewed images on the microlaser projector (the dots on left), than when they viewed images on the CRT (the dots on right). Filled dots mark proportions of errors for F-15s, and unfilled circles mark proportions of errors for F-16s.*

Another analysis of variance of the same design showed significant effects of *Plane Type* (F(1,14) = 12.84, $p \leq .01$) *Device*, (F(1,14) = 37.20, $p \leq .0001$) *Depicted Distance*, (F(2,28) = 59.16, $p \leq .0001$) and *Pitch* (F(1,14) = 56.08, $p \leq .0001$) on the dependent measure of ln response time (*ln seconds*). Response times to images of the larger F-15 aircraft were shorter on average than response times to the images of F-16 aircraft. Response times to images on the CRT display (mean for 1 nm: 1.08 ln sec; for 2 nm: 1.21; for 3 nm: 1.32) were longer than response times to images on the microlaser display (mean for 1 nm: 0.47 ln sec; for 2 nm: 0.66; for 3 nm: 0.81). In addition, as might be expected, images of a larger relative size that depicted aircraft at near distances were given a quicker response than smaller aircraft images.

Similarly, a six-way analysis of variance for the untransformed dependent measure of response time in seconds (*seconds*) revealed significant main effects of *Device*, ($F(1,14) = 33.10, p \leq .0001$) *Depicted Distance*, ($F(2,28) = 13.61, p \leq .01$) and *Pitch* ($F(1,14) = 9.50, p \leq .01$). The ln transformation applied to the dependent variable of response time does not alter the significance of these effects.

A six-way analysis of variance on the dependent measure of error of estimate in aspect (*cosine Δaspect*) showed significant effects of *Device*, ($F(1,14) = 26.28, p \leq .001$) *Aspect*, ($F(7,98) = 13.76, p \leq .01$), and *Pitch* ($F(1,14) = 15.15, p \leq .01$). There were also significant interaction effects of *Device x Aspect* ($F(7,98) = 18.58, p \leq .001$) and *Device x Pitch* ($F(1,14) = 16.85, p \leq .01$). Both devices showed some variation in estimates of orientation, that differed across the images. Perhaps surprisingly, the microlaser display that enabled quicker and more accurate identifications of aircraft was also the display that occasioned less accurate estimates of orientation. Figure 4 shows that observers had little bias in their average estimates of aspect with the CRT device. The average values of these estimates fall on or near a circle in the graph, which circle indicates zero error in estimate of aspect. With the microlaser device, the estimates of aspect are strongly biased, especially at aspects of 0° and 180° (where the plane is travelling directly towards or directly away from the observer). The interaction of device type and pitch is dramatic: though observers showed little error in aspect when using either device (microlaser: 0.02; CRT: 0.00), yet the same observers showed a large error in aspect when aircraft tilt was depicted by the microlaser device (microlaser: 0.21; CRT: 0.00). One may be reminded that this dependent measure involves estimates of aspect, not pitch. Observers showed a bias in estimate of aspect, in those conditions in which variations in pitch of the aircraft were depicted.

A six-way analysis of variance on the dependent measure of error in estimate of pitch (*cosine Δpitch*) showed a significant effect of *Device*, ($F(1,14) = 23.97, p \leq .001$). There were also significant interaction effects of *Device x Pitch* ($F(1,14) = 13.45, p \leq .01$), *Aspect x Pitch* ($F(7,98) = 12.03, p \leq .01$) and *Device x Aspect x Pitch* ($F(7,98) = 11.83, p \leq .01$). Again observers showed little or no bias in estimates of pitch with the CRT display, whether pitch was depicted or not (with no pitch: -0.01; with pitch: -0.03). Yet observers showed a strong bias in their estimates of pitch with the microlaser device, especially when some pitch was depicted (with no pitch: 0.15; with pitch: 0.25).

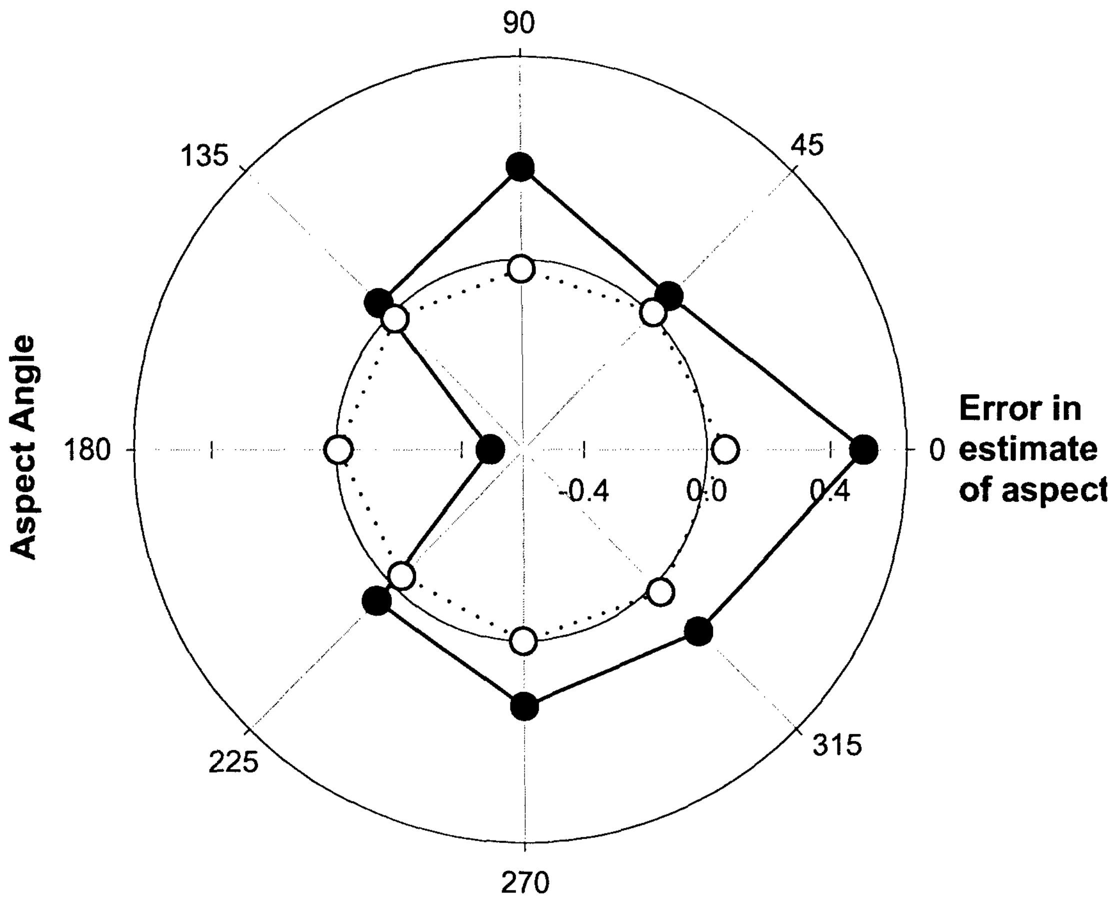

Figure 4. *This polar plot shows how errors in estimates of aspect depend on aspect angle in the picture plane. While estimates of aspect are largely unbiased with the CRT display, estimates of aspect are biased strongly with the microlaser projector. The direction of the aspect angle to be judged is shown by angle around the circle; the radius of this polar plot shows errors in estimate of aspect. The unit of error is the cosine of the estimated aspect angle minus the actual angle. An average error of zero is marked by a complete solid circle. Unfilled dots mark average errors for the CRT device; filled dots mark average errors for the microlaser projector.*

There are two qualitative observations that should be made about the results. The first concerns errors when aspect and pitch are combined, and the second concerns reversals. Estimates of the spatial orientation of the aircraft are worse for the microlaser projector than for the CRT device, when aspect and pitch are combined into a single estimate of angle in space. The measures of aspect and pitch can be combined into a measure of angular difference overall between the actual orientation and the estimated orientation. When the error in combined angle is plotted for the two devices, the average error over conditions of aspect is almost uniformly larger for the microlaser device than for the CRT. (The close exception is the error at aspect angles of 180°). Another qualitative observation may be made about full reversals in judgment of orientation. A reversal is coded in terms of the measures of the error measures of estimates of aspect and pitch: that is, in terms of 1) the difference of the cosine of the estimate of aspect and the cosine of the depicted aspect, and 2) the difference of the cosine of the estimate of pitch and the cosine of the depicted pitch. What counts as a reversal may not only be a reversal of exactly 180° in aspect. A tolerance is given, by which other estimates may be called reversals. A pure reversal has a value of –1.0. Some margin of error is given to this: the value of these dependent measures is allowed to range from –0.95 to –1.0 to count as a reversal. In terms of angle, this means about 20° on either side of the 180° which would count as a pure reversal. With this criterion, the number of reversals can be counted. Reversals prove to be a very common sort of error; they are the most frequent category of response after correct responses – that is, as the spatial orientation of the estimate is in question. The observation seems realistic in terms of the errors that pilots do commit: though the axis of a plane's motion may be apparent, the direction of its motion may not be apparent at first. Though reversal errors are common, there do not seem to be clear differences between conditions of plane type or device. For instance, though aspect reversals are more common with the microlaser projector than with the CRT display – 979 versus 887 of 11520 responses – yet reversals of pitch are less common with the microlaser projector than with the CRT display – 502 versus 717 of 11520 responses.

A convoluted discursion

One dependent measure can be singled out for a more extended discussion: there is a more thorough description of the response time data that can be given. Questions of the accuracy of observers' estimates are logically independent of questions about response time. Though the questions may seem to be related, say by a psychological theory that relates response times to the novel spatial orientations of familiar objects, the measures are independent. There is an account of the response times to identification that can be given in terms of the characteristics of these images of aircraft – that is, their characteristics as flat images in the picture plane. The notion of a convolution of gray-level images will be applied to describe the response-time results that have been obtained in this experiment on identification. At least for these data, response times may be accounted for without recourse to description of the aircraft images as they depict solids that are oriented in space.

Some readers may be acquainted with the operation of *convolution*, or more specifically with the convolution of two-dimensional matrices [14]. Two-dimensional matrices can represent the gray levels of images as integers that range from 1 (black) to 256 (white). Such matrices may also represent the gray levels of *binary* images, which take on values of 0 (black) and 1 (white). The array of pixels in an image can be represented as a matrix; the gray level of each pixel in the array is represented by an entry in the matrix. Our interest lies in operations on matrices of equal size: that is, in convolutions which are applied to two large matrices of a matching number of rows and a matching number of columns. The autocorrelation of a matrix is the same operation of convolution, applied to a matrix and itself. The convolution of two large matrices (or the autocorrelation of one matrix) has a still larger matrix as its product.

Let us begin with two gray-level images I_1 and I_2 ; each image is divided into a number of x columns and y rows. Our two images have the same numbers of rows and columns of pixels. We may express pixel locations or integer-valued coordinates on the images as $I_1(x,y)$ or $I_2(x,y)$. Each pixel – for example, $I_1(3,4)$ – is associated with an integer which represents the lightness of the pixel: with its gray level. Consider two new parameters j and k, that range over coordinate values (ie., over pixels) in the same way as the parameters x and y. Then the convolution $I_1 \otimes I_2(j, k)$ of the two images $I_1(x,y)$ and $I_2(x,y)$ can be written as:

$$I_1 \otimes I_2(\mathbf{j}, \mathbf{k}) = \sum_{x=0}^{x=n-1} \sum_{y=0}^{y=m-1} I_1(\mathbf{x},\mathbf{y}) \bullet I_2(\mathbf{j}-\mathbf{x}, \mathbf{k}-\mathbf{y})$$

where $\mathbf{j} = 0, 1, \ldots, n-1$; $\mathbf{k} = 0, 1, \ldots, m-1$.

And when $I_1(x,y)$ and $I_2(x,y)$ are the same image, the autocorrelation statistic r_c is then:

$$r_c = (2m-1)^{-1}(2n-1)^{-1} \sum_{j=0}^{j=n-1} \sum_{k=0}^{k=m-1} I_1 \otimes I_2\,(\mathbf{j}, \mathbf{k})$$

The statistic can be *interpreted* as an index of the similarity of two gray-level images, if the two images are not the same. This contrasts with other views of the similarity of such gray-level images [15, p.150] which treat pictures of military fighter aircraft in a very different way. They proceed from the cluster analysis of similarity ratings by observers, rather than from properties of pictures themselves. For a binary image this statistic (that is, the autocorrelation statistic of the image and itself) has a familiar property: it is proportional to the area squared of a white-on-black silhouette. The autocorrelation statistic is in a sense an optical property: it bears a physical interpretation in terms of the propagation of light, as does the operation of convolution.

The stimuli for the experiment on aircraft recognition were 96 distinct images of F-15 aircraft and F-16 aircraft. The images were cropped to a format of 300 x 300 pixels, since the background of all the images was a homogeneously bright sky. The aircraft profiles were wholly contained in these cropped versions, though the aircraft profiles were not always centered within the image frame. (The value of the autocorrelation statistic does not change with the translation of a single object across the homogeneous background of the image.) The gray-levels of the images were reversed, from values between 1 and 256, to values between 256 and 1, so that the bright sky appeared as a dark background. To create a binary version of each image, a lightness threshold was assigned (there is a wide range of thresholds that would have created silhouettes: the number 26 was chosen). The resulting binary images are detailed white-on-black profiles of the aircraft at each orientation and distance. (Figure 5 provides some examples.) The average gray levels of these autocorrelations of these 96 binary images were computed; in other words the square of the area was computed for the region within the outline of these aircraft. The ln values of the autocorrelation statistic were compared to the log-transformed response times for the corresponding conditions. The calculations were performed on bitmap files and not on images from the projection screen. That is to say, effects of artifacts introduced by the projection devices are not incorporated in the calculations.

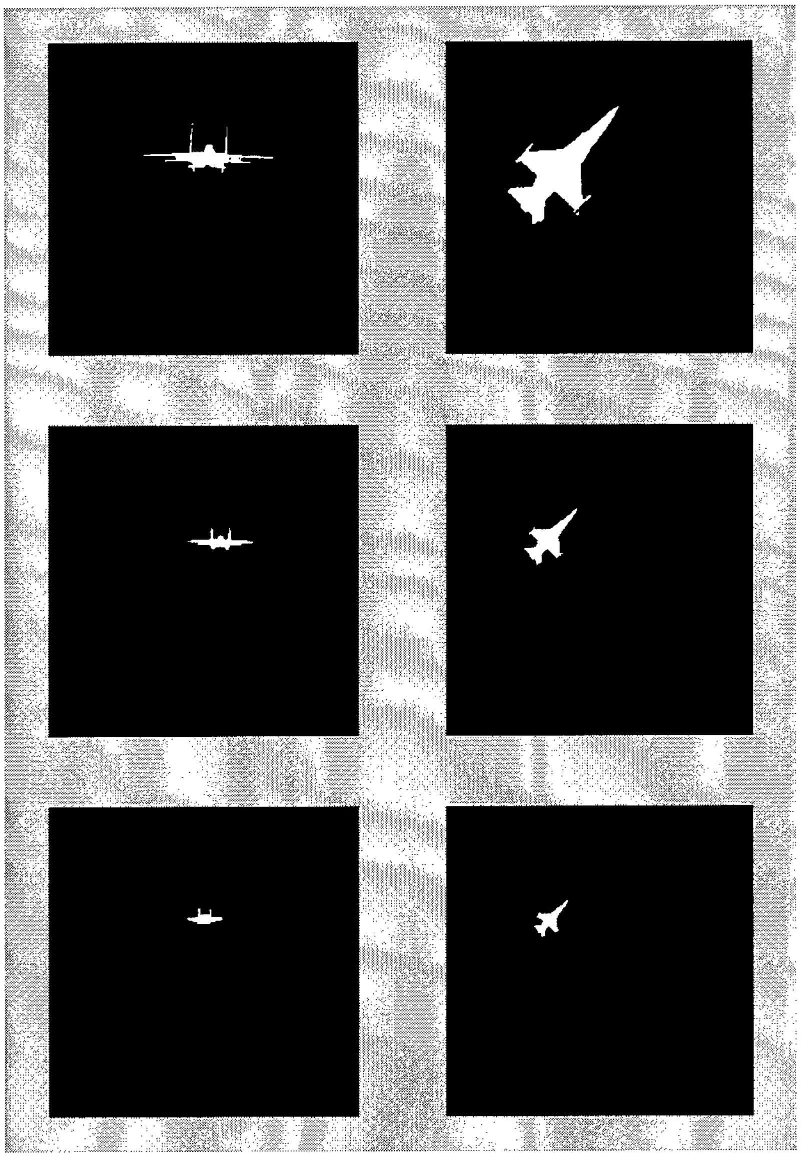

***Figure 5.** Images of the F-15 and F-16 aircraft were processed in order to derive aircraft silhouettes. First the contrast of the images was reversed. Then the images were subjected to a thresholding operation. Here are two types of silhouettes; from top to bottom they vary in three levels of depicted distance. These images were convolved with themselves, and the average gray level of the resulting convolution was computed.*

At first, response times were averaged over the fifteen subjects, which means that the number of observations then corresponds to the number of conditions in the experiment for a subject, namely 768. Response times for one display device – the laser projector – are notably shorter than for the other – CRT – display device. The trend is illustrated in Figure 6. A multiple regression was performed, with ln response time as the dependent variable. The autocorrelation statistic and the device type (a dummy variable coded as 1 or 2) were independent variables. The R statistic of the multiple regression equation is 0.89 ($F(2,765) = 1491.2$, $p \leq .001$); it indicates a linear association of the ln autocorrelation statistic with ln response time. That association is modified by a fixed difference in response time between the two devices. Loosely stated, we can account for recognition times by the relative area of the splotch that an aircraft makes on the display screen. The area squared of that silhouette is a variable that fits response times in a least-squares sense, despite changes in aircraft type, standoff distance, and the spatial orientation of the aircraft.

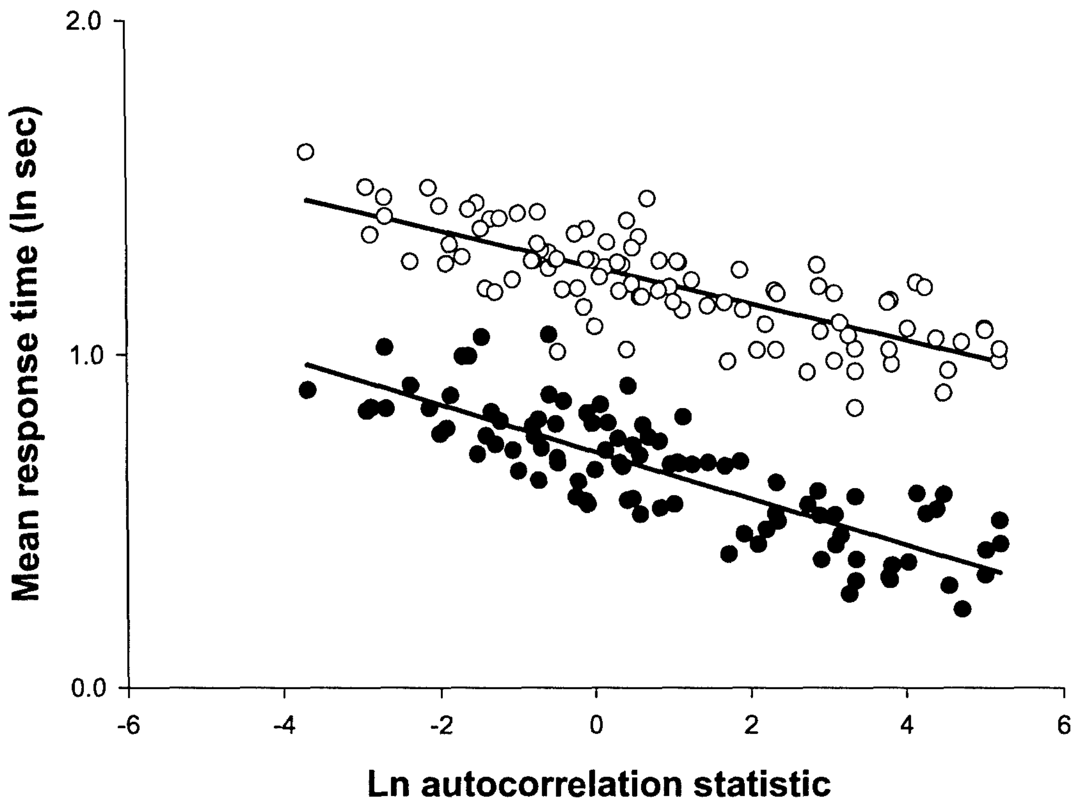

__Figure 6.__ A regression plot illustrates the relation between mean response time and the autocorrelation statistic for the response time data of the experiment. Filled circles represent data for the microlaser projector; open circles represent data for the CRT display. Each of these dots represents the data for all observers on one aircraft image. These data points are also averaged over the location on the screen at which the image appeared (top, bottom, left, or right), only for the purpose of the graph. Regression lines are drawn among the data points for each display device.

This pattern of response times is associated with accurate discrimination of the two aircraft. Those observers who are more accurate are also those who exhibit the pattern more strongly. The ln values of the autocorrelation statistic were compared to the log-transformed response times for each observer. That is to say, response times were no longer averaged over the 15 observers for the purposes of regression analysis. Rather 768 response times were examined separately for each of the 15 observers. A multiple regression statistic $\underline{R}$ was computed for each, with ln response time as the dependent variable. Just as before, the autocorrelation statistic and the device type were independent variables. There was a strong positive relation between the multiple $\underline{R}$ statistics and $\underline{d}$' measures of sensitivity for the fifteen observers (Pearson correlation: $\underline{r} = 0.82$). This positive relation was not affected by a restriction of range: the multiple R statistic ranged from 0.82 to 0.08 among the observers. Perhaps more familiarly, there is a strong negative association between the multiple R statistics and numbers of errors that the observers committed on 768 trials ($r = -0.81$; Spearman rank $r = -0.63$, $t(13) = -2.90$, $p \leq .05$). A correlation of response time with the area of the splotch projected by an aircraft has been found for individuals in the experiment. The more accurate the performance of those individuals, the stronger a correlation they exhibit.

We may compute the relative area contained in a silhouette, and find that response times to identification are correlated with the square of that area. But what can this tell us about the relation of response times to changes in depicted distance and slant ? The silhouettes in such binary images change with the distance and slant of the pictured aircraft. Though these distances and slants may not be recovered directly from the picture plane, still their effects may be known from changes in the convolution of the binary images. That is, their effects are known from changes in the areas of sections of a solid angle between object and image plane. Convolution is a plane operation: it has no unequivocal relation to the standoff distance of a pictured object from the image plane, just as it has no unequivocal relation to the slant of a flat object with respect to the image plane. Yet some quantitative effects of changes in distance and slant will appear as changes in the image plane [16].

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Discussion and conclusions

'I feel I'm ready for my tea,' Mrs. Hurstpierpoint reflected, taking up an invalidish posture on the jaguar-skin couch [17, p.53].

Some clear differences have been observed between the display devices. A definite prediction can be drawn for response times to the identification of the aircraft, as well. There are several specific conclusions that can be drawn from the results. They are:

1. Observers identified F-15 and F-16 aircraft more accurately with the microlaser projector than with the CRT display.

2. Observers identified the aircraft more quickly with the microlaser projector.

3. When the aircraft were varied in aspect alone, F-16 aircraft were identified far more accurately overall. When the aircraft were varied in aspect and pitch together, this was not the case.

4. It took more time to identify aircraft when they were depicted to be further away.

5. Reversal errors were common in observers' judgments of aspect and pitch.

6. Despite its other advantages, the microlaser projector biased observers' judgments of aspect angle. This bias was pronounced when pitch was varied together with aspect angle.

7. Combined error in aspect and pitch was larger for the microlaser projector than for the CRT display.

8. Response times to identification of the aircraft vary neatly with a statistic on the autocorrelation of the aircraft silhouettes. This pattern is stronger for observers who identify the aircraft more accurately.

9. Estimates of aspect angle and pitch are largely uncorrelated with response times and the frequency with which the aircraft are correctly identified.

Observers who estimate the orientations of depicted planes with the microlaser projector have large biases in their estimates of orientation: it is not yet clear which properties of the microlaser display may be responsible for these biases. There are two likely candidates. One of these is particular to this prototype display; the other is general to parallel-write displays. The former is a subtle sort of artifact due to the integration of information on the display over very short intervals. That artifact is characteristic of displays in which a frame is written in many bands, by several lines at one time. The latter is the kind of plain artifact that may be occasioned by interline differences in brightness. That kind of artifact may be occasioned by an element of the light valve that is nonfunctional, or which reflects or transmits less light than its neighbours. Displays that write an entire line or column of imagery at one time may have the second sort of artifact, but they do not have the first.

The main results of the analyses are that the microlaser projector contributes to fast and accurate identification of the aircraft. At the same time the microlaser projector seems to introduce a bias in estimates of orientation, which is unexpected. This bias in orientation occurs both in aspect and in pitch; it can be seen in the combination of the two. Clearly, some aspect of the laser projection system is having an unwanted effect. Whether this is the effect of the 64-line scan architecture, or an effect attributable to distortion at the level of an image frame, is a question that cannot be addressed by these data. Though the technology of microlaser projectors promises great improvement in pixel count, close attention should be paid to the measurement of direct estimates of spatial orientation when orientation is depicted by such a display. The validity of an observer's estimates of orientation should not be inferred from the observer's response times, or the frequency of correct responses.

The relative sizes of the silhouettes of the aircraft account for variations in response time to identification. In explanation of the Shepard-Metzler effect [18, 19] response times have been thought to track a mental process of rotation by which pictured shapes may be either identified or compared in three dimensions of space. So under that explanation, response times might vary with the pictured orientation in three dimensions of these aircraft. Yet the silhouette areas of these irregularly-shaped and self-occluding aircraft do not vary simply with their three-dimensional orientation. An outline profile seems a simpler thing, both accessible and quantifiable. It is accessible in the image plane, and its relative area is quantifiable by an autocorrelation statistic.

How can the present evidence – which associates response times with outline profiles – be reconciled with the apparent correlation of response times and differences in three-dimensional orientation? One way is to question the assumption that response times are associated with differences in three-dimensional orientation: it may be the case that other properties which are measurable in the image plane may account for this correlation. In other words, the association between response times and differences in three-dimensional orientation is an association mediated by an intervening variable. This third variable can be measured in the image plane, and that operation of measurement begins with the operation of convolution. As psychologists, we are prone to mistake properties of the environment for properties of the mind; physical properties for psychological predicates; and properties of what is seen or else properties of the medium of sight for properties of the visual system. Ashworth and Dror [15, p.156] claim that: "Explication of the cognitive factors underlying aircraft identification provides insight into the nature of, and processes associated with, the representations used to identify real-world objects." That may be true, but it may be that the evidence of response times does not address those cognitive factors. How aircraft can be identified, how quickly they can be identified, and how well their orientation in space can be discerned: these are three separate questions. The evidence of response times addresses the second question, but it may not touch the first and third. The pattern of response times associated with the identification of aircraft may depend on stimulus factors which are only incidental to spatial reasoning, and to categorization in cognitive terms.

The natural extension of the present investigation is to move from the judgment of static properties to the judgment of properties of moving aircraft. A subsequent investigation should involve stimuli that are significantly more complex than this initial investigation with static profiles. The stimuli are more complex in the sense that dynamic properties are to be judged rather than static ranges and aspect angles alone. The operational judgments that must be made with a simulator display include not only aspect angle and range, but also range rate and aspect rate (that is, dynamic change in range and change in aspect). Other dynamic properties are rate of 'angle off' (related to heading), and changes or acceleration in closure. This degree of sophistication in an experiment begins to match the complexity of the task required of the operator in the simulation for which the display is intended.

There are many factors that operate in the identification of aircraft, which have not yet been controlled in experiment. The characteristics of devices by which responses can be registered may change the expression of competence by observers. Auxiliary factors such as the power characteristics of aircraft may help to identify aircraft, as contrails and glint may help to detect them. There are a number of ways the present findings can be verified and extended. An obvious way is to repeat some of these tests on new versions of microlaser displays: that work is in preparation. Another is to extend the testing from the perception of static aspect to the perception of aspect rate – to show the target aircraft in rotational motion. With the development of new microlaser displays, we can show the images of aircraft at small subtenses of visual angle, to match the subtense of a plane at many kilometers. These displays are promising, since new scan patterns can be engineered for future microlaser projectors. Also, the hypothesis of the relation between response times and statistics on the convolution of silhouette images needs to be verified and extended to many aircraft types. A good way to start would be to vary the aspect and pitch of the target planes randomly, in other words to make them random variables over the sphere for the purposes of an experiment. The present effort has been only a preliminary investigation, a first foray, into laser projection and the identification of aircraft by eye.

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Annex A
Definition of aspect angle

Warner, Serfoss, and Hubbard [7] provide a definition of aspect angle. "Aspect angle is defined as the angle formed by the target's flight path and the line of sight from the attacker [KN: the observer] to the target when measured from the tail of the target aircraft. Aspect angle can vary from 0 to 180 deg. For example, at 0-deg aspect, the target is tail-on to the attacker; at 180-deg aspect, the target is nose-on to the attacker; at 90-deg aspect, the long axis of the target is perpendicular to the attacker's line of sight. Aspect angle changes as the target changes heading; it is not affected by the attacker's heading." The effect of this definition is shown in Figure 7. There variations in aspect angle and pitch are shown as directions along rays from the origin in an obliquely-projected x,y,z coordinate system. Six orientations in the form (aspect angle, pitch angle) are shown aligned with coordinate axes. An orientation of (0, 0) represents an orientation perpendicular to the plane of the picture plane, pointing away from the observer. When pitch is equal to 90° or -90°, nominal variations in aspect angle do not affect overall orientation: hence the variable 'y' for the aspect angle of those orientations.

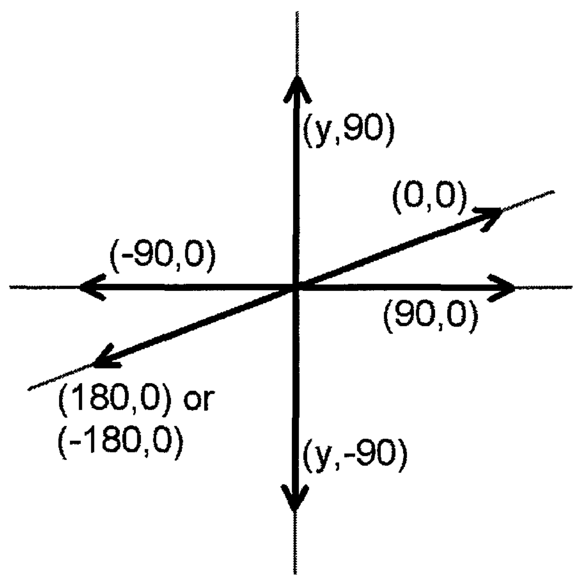

Figure 7. *Variations in aspect angle and pitch are shown as directions along rays from the origin in an x,y,z coordinate system. Six orientations in the form (aspect angle, pitch angle) are shown aligned with coordinate axes. Aspect angle ranges from -180° to 180°; pitch angle ranges from 90° to 90°.*

DOCUMENT CONTROL DATA SHEET

1a. PERFORMING AGENCY	2. SECURITY CLASSIFICATION
DRDC Toronto	UNCLASSIFIED Unlimited distribution -
1b. PUBLISHING AGENCY	
DRDC Toronto	

3. TITLE

(U) A foray into laser projection and the visual perception of aircraft aspect

4. AUTHORS

Keith K. Niall

5. DATE OF PUBLICATION	6. NO. OF PAGES
April 1 , 2002	29

7. DESCRIPTIVE NOTES

8. SPONSORING/MONITORING/CONTRACTING/TASKING AGENCY

Sponsoring Agency:
Monitoring Agency:
Contracting Agency :
Tasking Agency:

9. ORIGINATORS DOCUMENT NO.	10. CONTRACT GRANT AND/OR PROJECT NO.	11. OTHER DOCUMENT NOS.
Technical Report TR 2002-108	PWGSC file W7711-7-7407	

12. DOCUMENT RELEASABILITY

Unlimited distribution

13. DOCUMENT ANNOUNCEMENT

Unlimited announcement

14. ABSTRACT

(U) High-resolution visual displays have been designed for flight simulation so that observers may judge the aspect angle of aircraft at far distances. The present experiment compares two display devices as untrained observers judge the spatial orientation of two target aircraft: F15 and F16 jets. The display devices are a prototype direct-write microlaser projector, and an SXGA format CRT display. Observers' accuracy of aircraft identification is better with the laser projector, and recognition response times are faster. A simple rule was found to fit the observers' response times: the rule is expressed in terms of a statistic on the autocorrelation of black and white silhouette images of aircraft. Observers' estimates of aspect are biased by the laser projector, while observers' estimates of aspect are accurate on average with the SXGA display. This bias in estimation of aspect may be attributable to variations in line brightness introduced by the laser projector.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U)

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